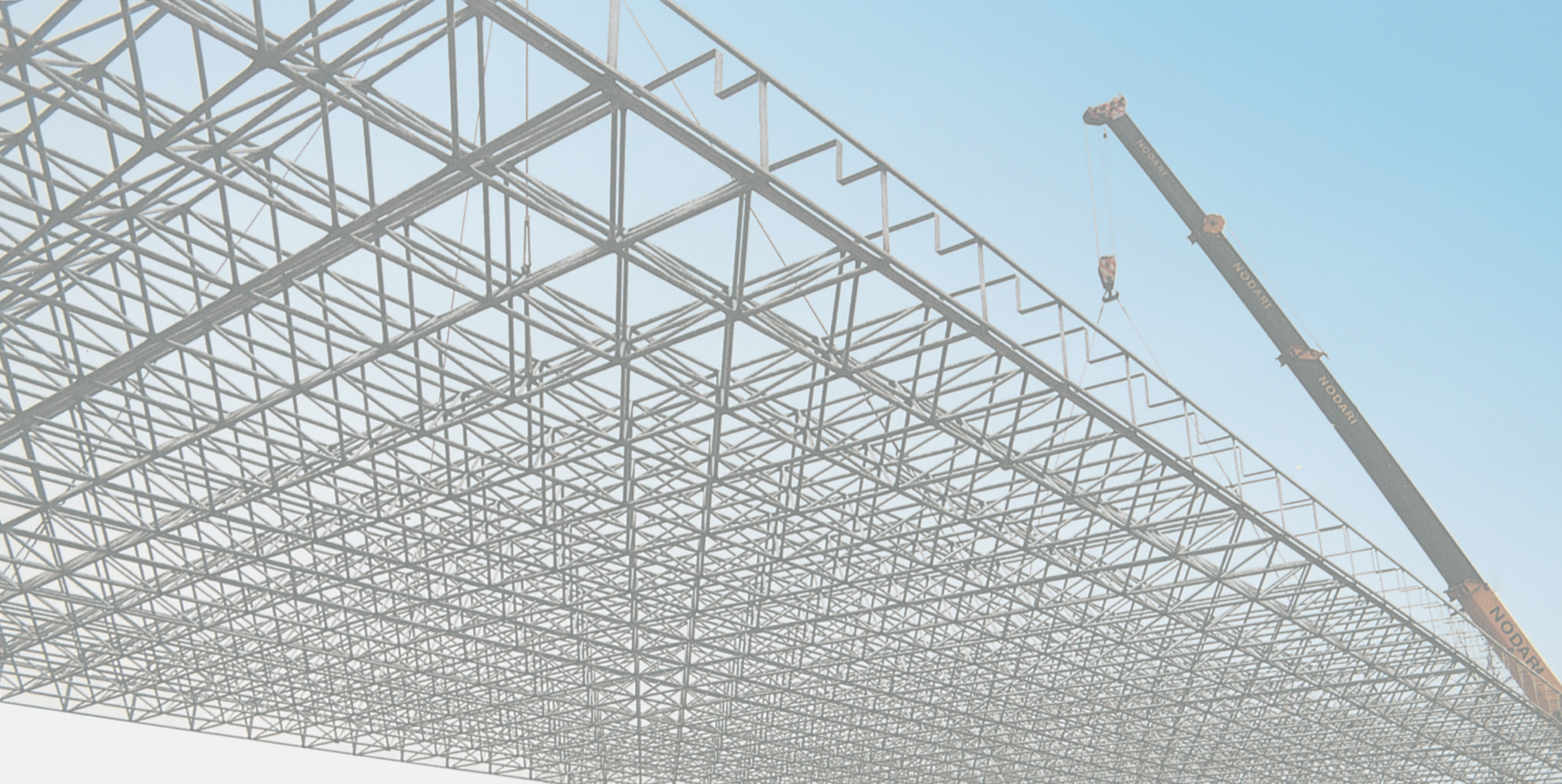

Perspectives on High Resolution Modeling

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Seamless Prediction <u>Science</u> Questions Are Model- and Resolution-Dependent!

What limits predictability at all time scales from days to decades?

Bony et al. 2015:

- **Roles of convection, convective aggregation and cloud feedbacks?**
- **What controls the position, strength and variability of storm tracks?**
- **What controls the tropical rain belts?**

Hawkins and Sutton 2009:

- **How do initial state, coupling of system components, and changes in external forcing contribute to predictability?**

What is the role of model error and what is the optimal resolution and ensemble size/composition to predict <u>means</u>? <u>Extremes</u>?

- **No current models are perfect, e.g. for regional water cycle**

Models, Resolution and Computing

- **Numerical Weather Prediction (NWP)** critically depends on ever-increasing capability and capacity for computing and data
- **Numerical Climate Simulation and Prediction (NCSP)** likewise depends on high-performance computing and "Big Data" resources

Exploiting HPC

- **ENIAC to Titan**: 7 decades of computing advances
  - 1946: 357 FLOPs - dawn of stored-program computing
  - 2016: 27 X 10^{15} FLOPs (petaflops) peak on 299K cores
  - What have we done with accelerating HPC power?
- **NWP**: Enormous progress, due to
  1. **Increasing model resolution**
  2. Better representation of relevant processes
  3. Data assimilation methods
- **NCSP**: Much more modest progress in spatial resolution in climate models; **added components and processes** instead

Spatial Resolution

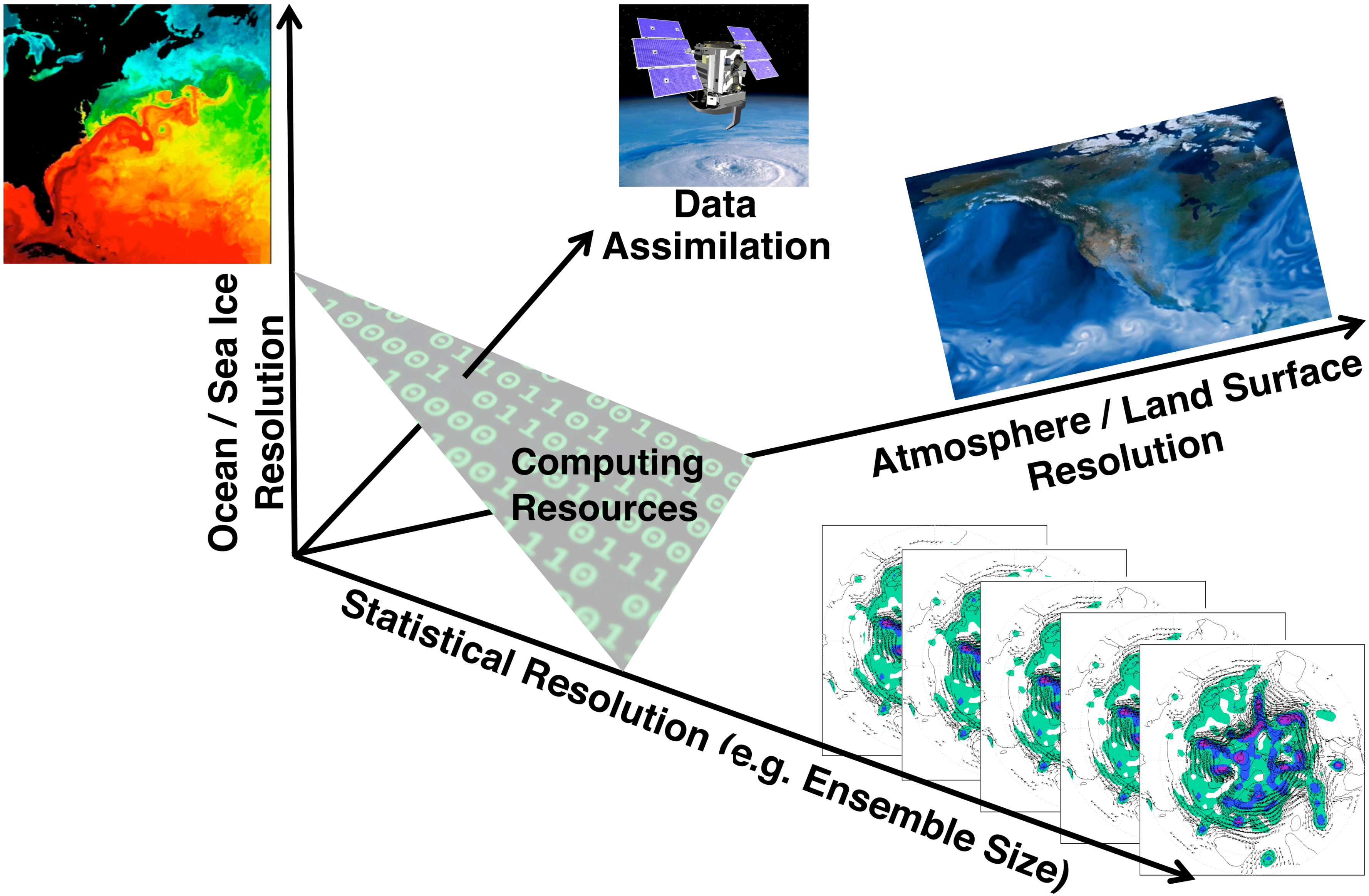
- **We expect numerical solutions to converge to the continuous solution as we refine the grid**
  - Numerical solutions of continuous PDEs improve as we reduce/eliminate approximations inherent in discretizing/ filtering
- **How much refinement is "enough"?**
  - It is not practical, and likely not scientific (due to Brownian motion), to attempt to **track every *kmol*** (~10^{26} molecules), of substance in the Earth system
  - On the other hand, a model that **tracks only the largest scale features** is clearly inadequate

- **What are the "breakpoints" or thresholds in resolution** between these extremes, and are there indications that we make gains by reaching those breakpoints?

Spatial Resolution – Practical Matters

- Are there **relative benefits** to resolving the atmosphere, the ocean, the land surface or other aspects better?
- Are there **issues with ratio of vertical to horizontal** grid spacing (Lindzen & Fox-Rabinovitch 1989)?
- What **new issues** arise when resolution is increased?
  - Example: Eddy-resolving ocean model may have multiple gridpoints at the mouth of a large river → where does the runoff get deposited?
- **Trade-offs in model configuration** with given computing resources
  - Example: Which has higher priority - ocean eddies or tropical cyclones?
  - What is best thing to do with 10X more computing?

Balancing Demands on Resources

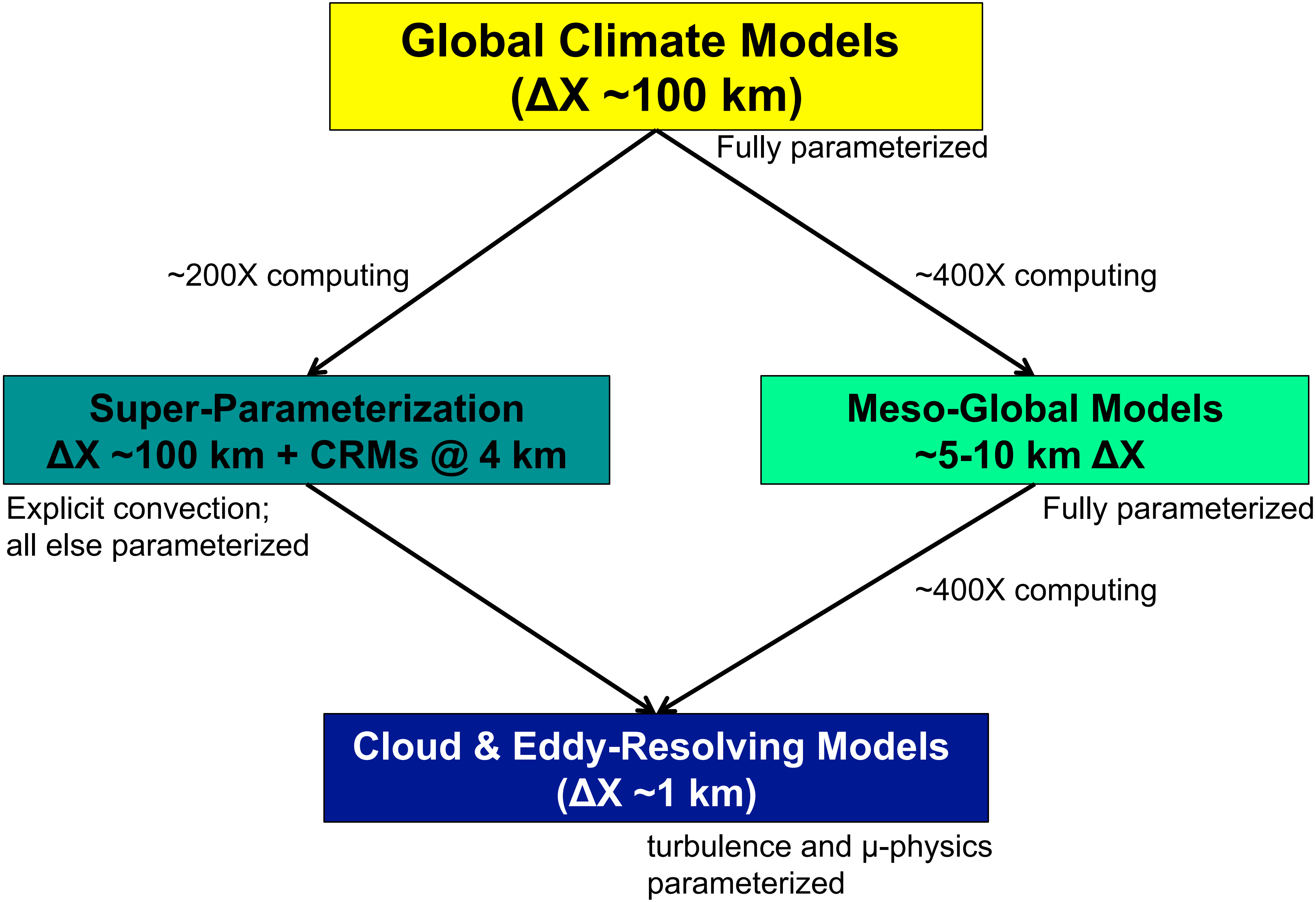


Resolving vs. Parameterizing

- Any discretization/filtering scheme **implicitly or explicitly discriminates resolved scales from unresolved scales**
  - Resolved: Features of size 5-10 ΔX
- **Rectified effects of unresolved scales on resolved scales can be first order**
  - Due to second law of thermodynamics, irreversible processes, and dynamical nonlinearity
- **Parameterizations**
  - Represent rectified effects of unresolved scale processes on the resolved scales
  - **Generally local, diffusive and equilibrium-restoring**
  - Do not adequately represent processes that are **non-local or latent, up-gradient, or unstable locally in space or time**.
  - In general, a parameterization that frequently exhibits the latter properties would be **numerically unstable**.

Parameterized Processes (examples)

- Atmosphere
  - Cloud formation, development and demise (see Bony et al. 2015) and organized convection
  - Turbulence (including mixing by motions whose scales are ≤ a few ΔX)
  - Cloud μ-physics (including aerosols as CCN)
- Land surface
  - Groundwater flow, both vertically and laterally
  - Heat exchange between soil layers and deep layers
- Ocean
  - Mixing by eddies
  - Turbulence (including organized turbulence, e.g. langmuir circulation)
- Sea ice
  - Leads, floes, ponding, pressure ridges, anisotropy
- Coupling
  - Non-local effects of gradients in land surface properties on atmospheric circulation & rainfall
  - Sea spray as source of CCN
  - Sub-shelf heat and freshwater flux impacts on iceberg calving and ice shelf dynamics
- Other processes
  - Vegetation dynamics
  - Radiative and energetic effects of algae in upper ocean, sea ice
  - Biogeochemical cycles (C, N, OH, …)


Global Climate Models
(ΔX ~100 km)
Fully parameterized
~200X computing
~400X computing
Super-Parameterization
ΔX ~100 km + CRMs @ 4 km
Explicit convection;
all else parameterized
Meso-Global Models
~5-10 km ΔX
Fully parameterized
~400X computing
Cloud & Eddy-Resolving Models
(ΔX ~1 km)
turbulence and μ-physics
parameterized

“Meso-global” Models

- **Meso-global coupled climate models** (ΔX ~ 5-10 km) resolve all dynamical and physical processes and phenomena with spatial scales at, and larger than “mesoscale,” including:
  - Tropical and extra-tropical storms
  - Oean eddies
  - Catchment-scale flows
  - Ice floe distributions
- They include parameterizations of sub-grid scale physical processes such as convection, ocean mixing

Why Do We Need Meso-Global Models for Prediction?

- **Societal demand for information about weather-in-climate and climate impacts on weather**
- **Seamless days-to-decades prediction & unified weather/climate modeling**
- **Process-scale interactions**
- **Data assimilation at scale of observations**

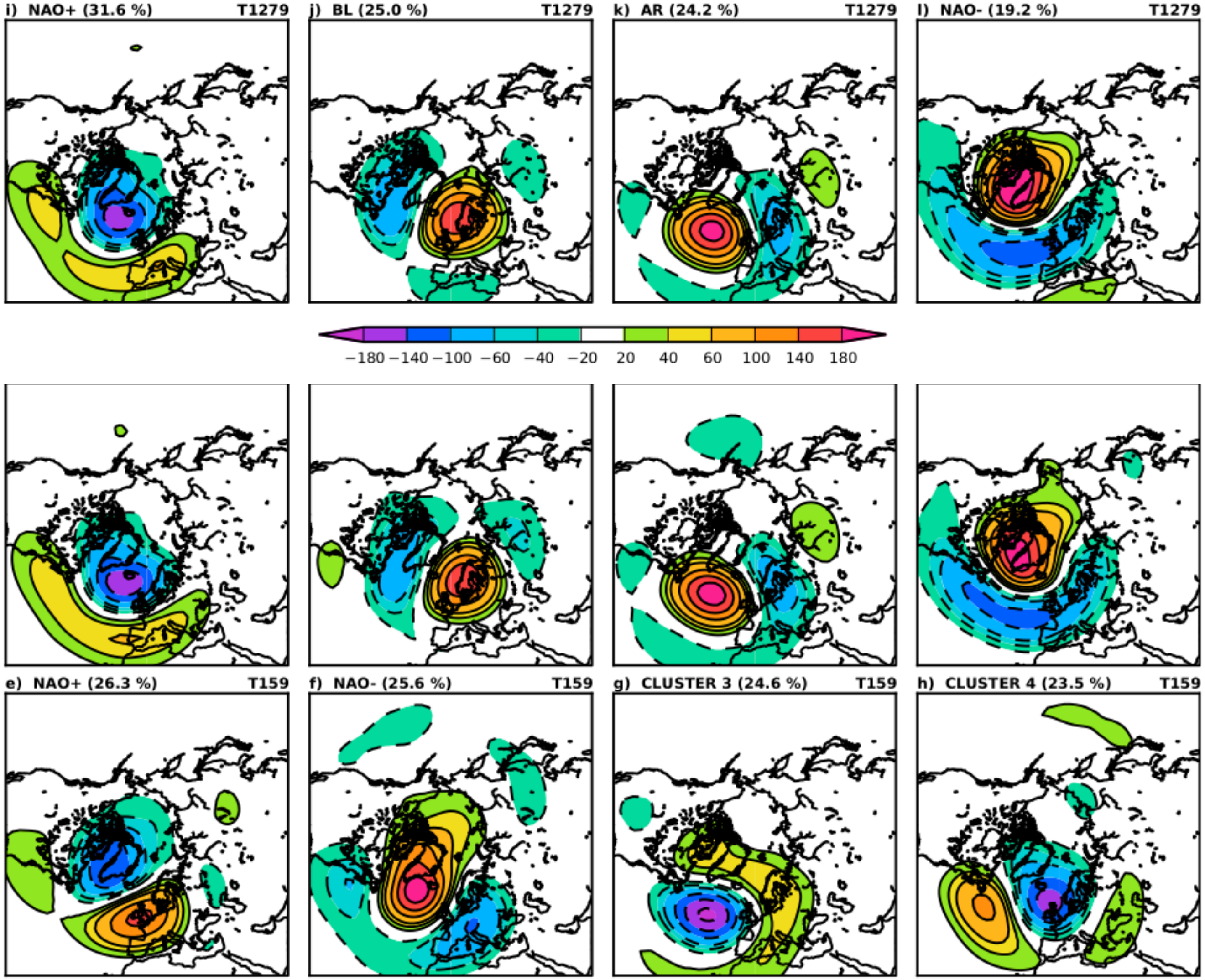
Examples

Athena: Regime Structures

T1279

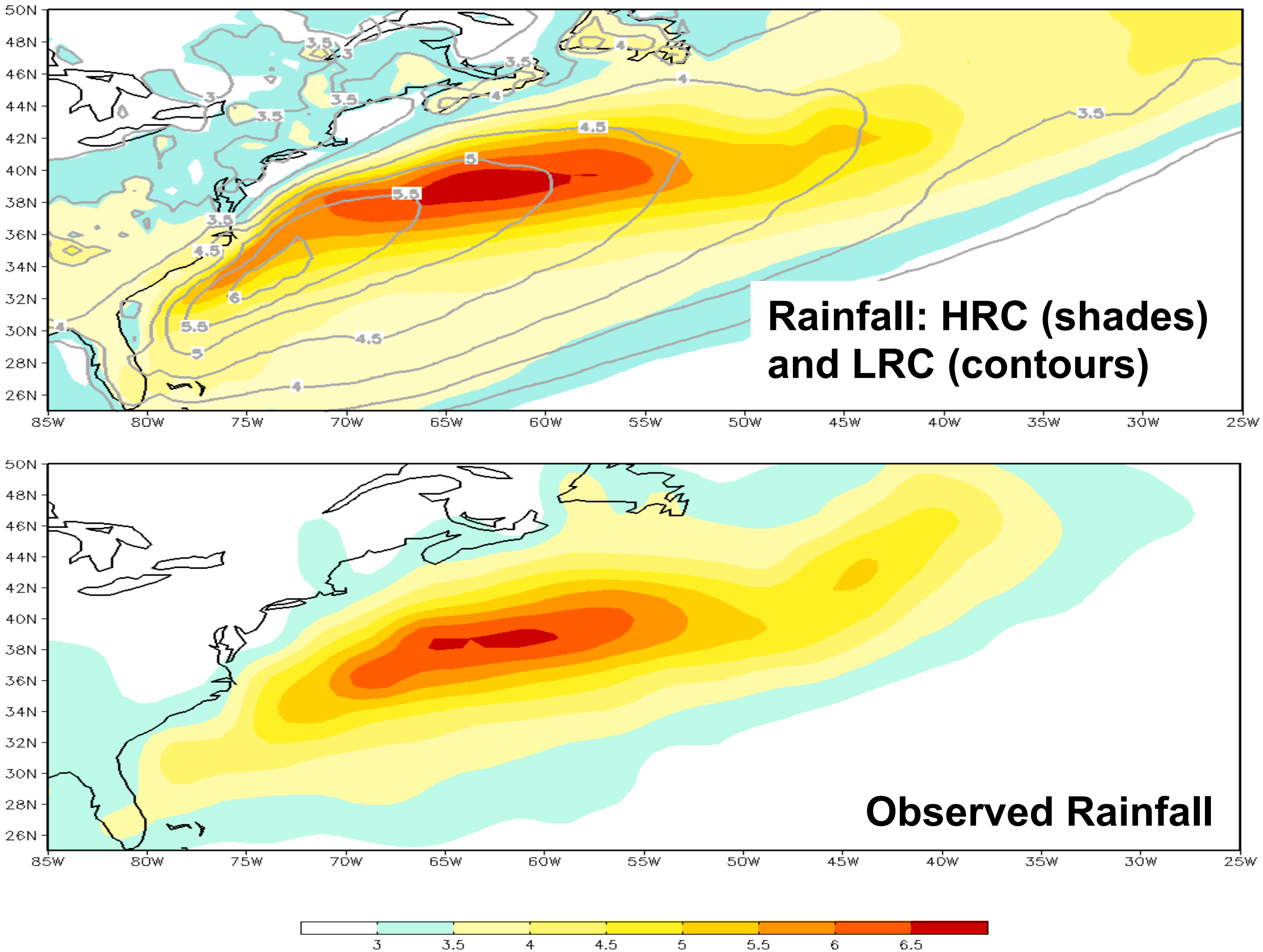
ERA-I

T159



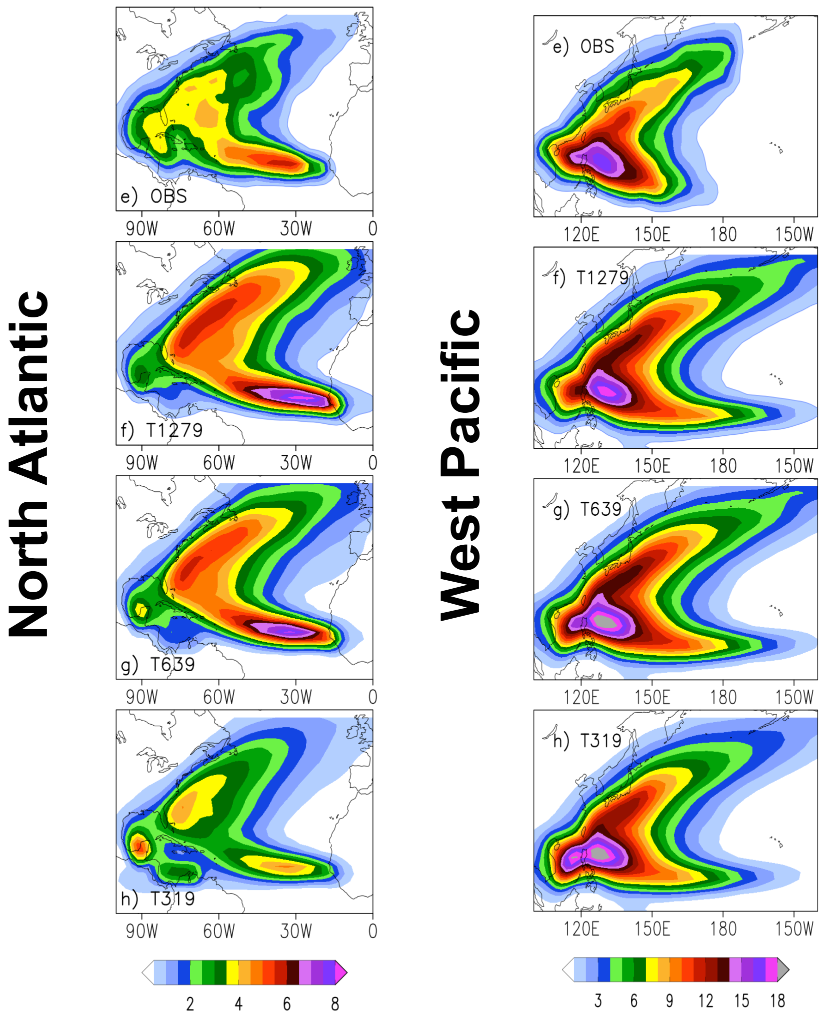
Dawson et al. 2012

PetaApps: Rainfall Simulation

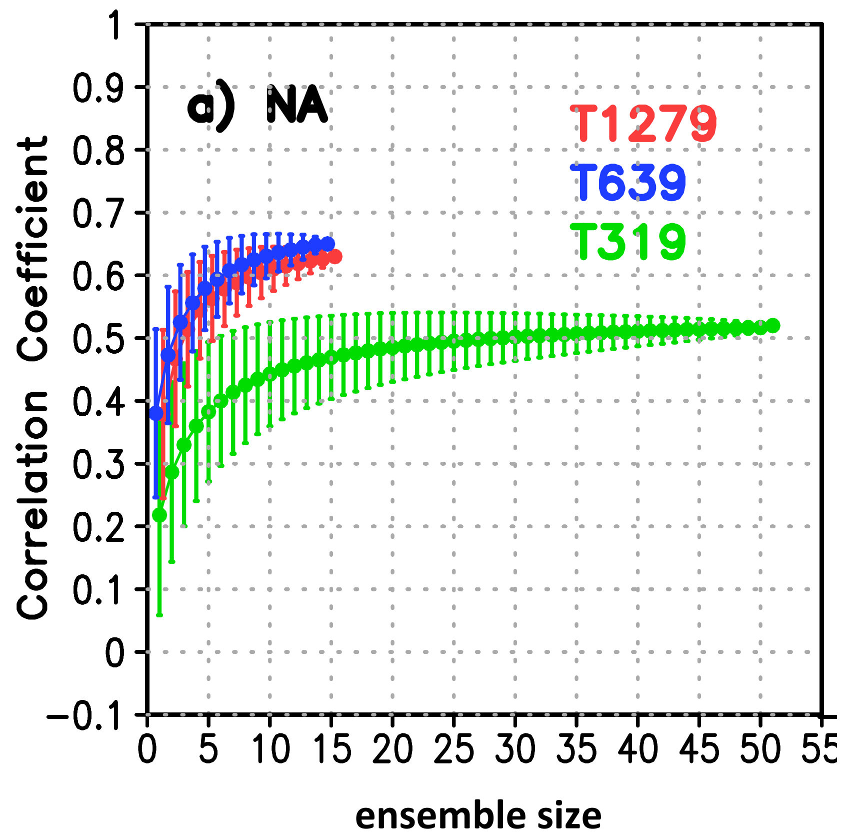


Minerva: Coupled TC Forecasts

TC Track Density



ACE Forecast Skill



Manganello et al. 2015

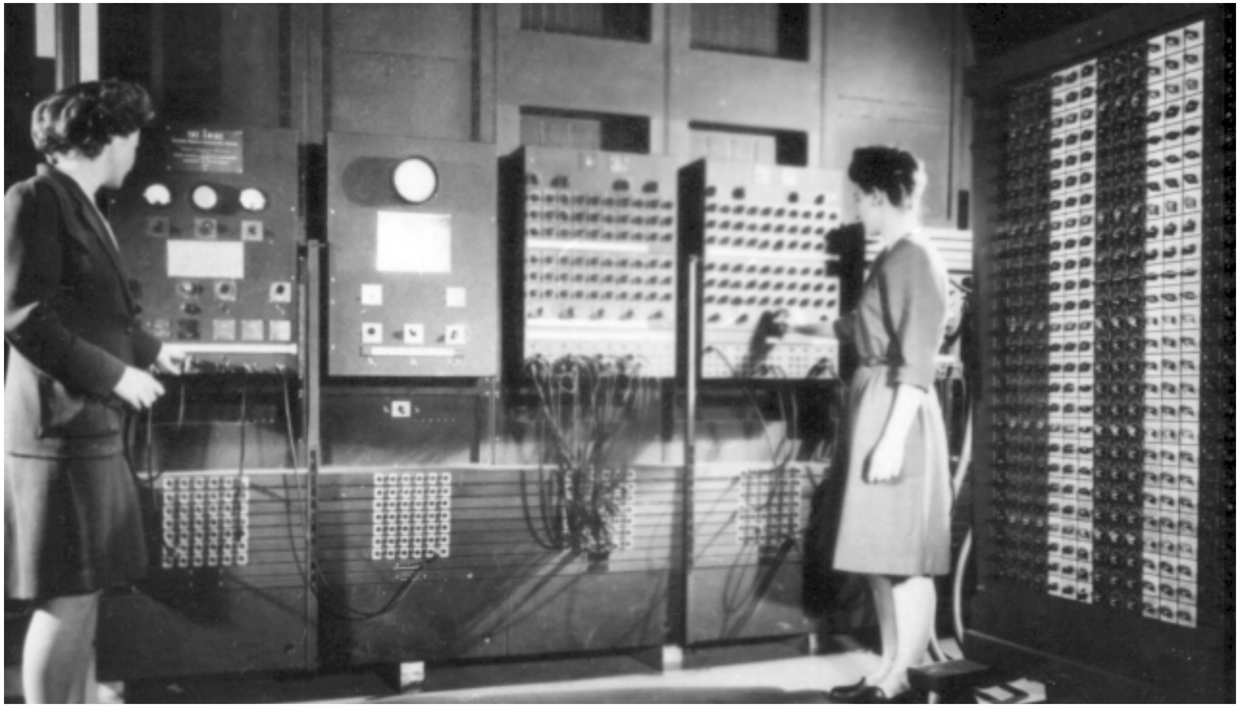
Issues: Science Gaps*

- Increasing spatial resolution is not a panacea – why not?
- Threshold behavior at a grid spacing of 50 km in several independent models - Why? Is there a systematic way to address this question?
- Gray zones: global atmosphere (4-10 km), PBL and clouds (1 km), ice floes (10 km), … → scale-aware parameterization?
- Much long-term bias can be ascribed to fast physics errors … BUT … some biases develop only at long model integration times
- Missing physics – should parameterizations simply be stochastic?
- Traditional diagnostics don't necessarily elucidate errors in process representation
- Observing systems: Are we extracting all available information out of the observing systems for initializing and validating meso-global coupled models?

(*) Based on discussion at 2015 DOE-NOAA Workshop on High-Resolution Coupling and Initialization to Improve Predictability and Predictions in Climate Models

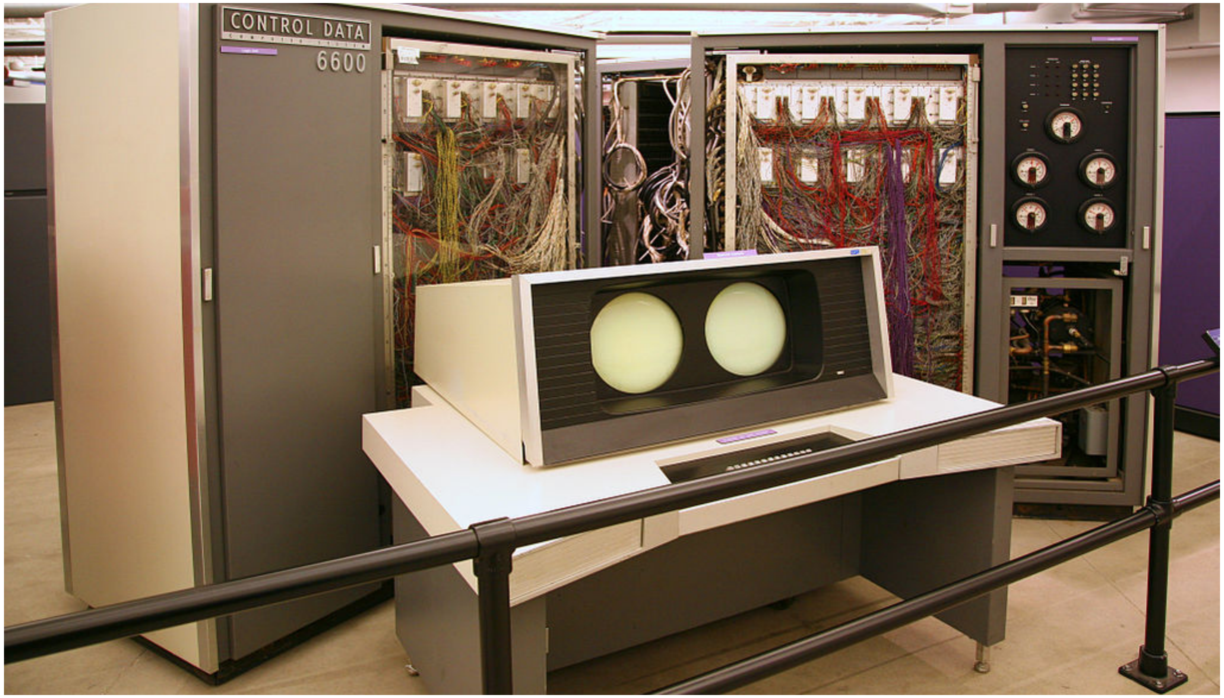
Questions?

1940s High-Performance Computing (a.k.a. "Computing")



- Programmers Betty Jean Jennings (left) and Fran Bilas (right) operate ENIAC's main control panel at the Moore School of Electrical Engineering. (U.S. Army photo from the archives of the ARL Technical Library).
- ENIAC floating point speed: 5000 cycles per second → 357 FLOPs (10 digit multiply).
- **First NWP forecast made in less than real time in 1950**

1960s HPC: Supercomputing



- CDC 6600 introduced 1965 with peak speed of 3 MFLOPs
- **~ 8000 X ENIAC**

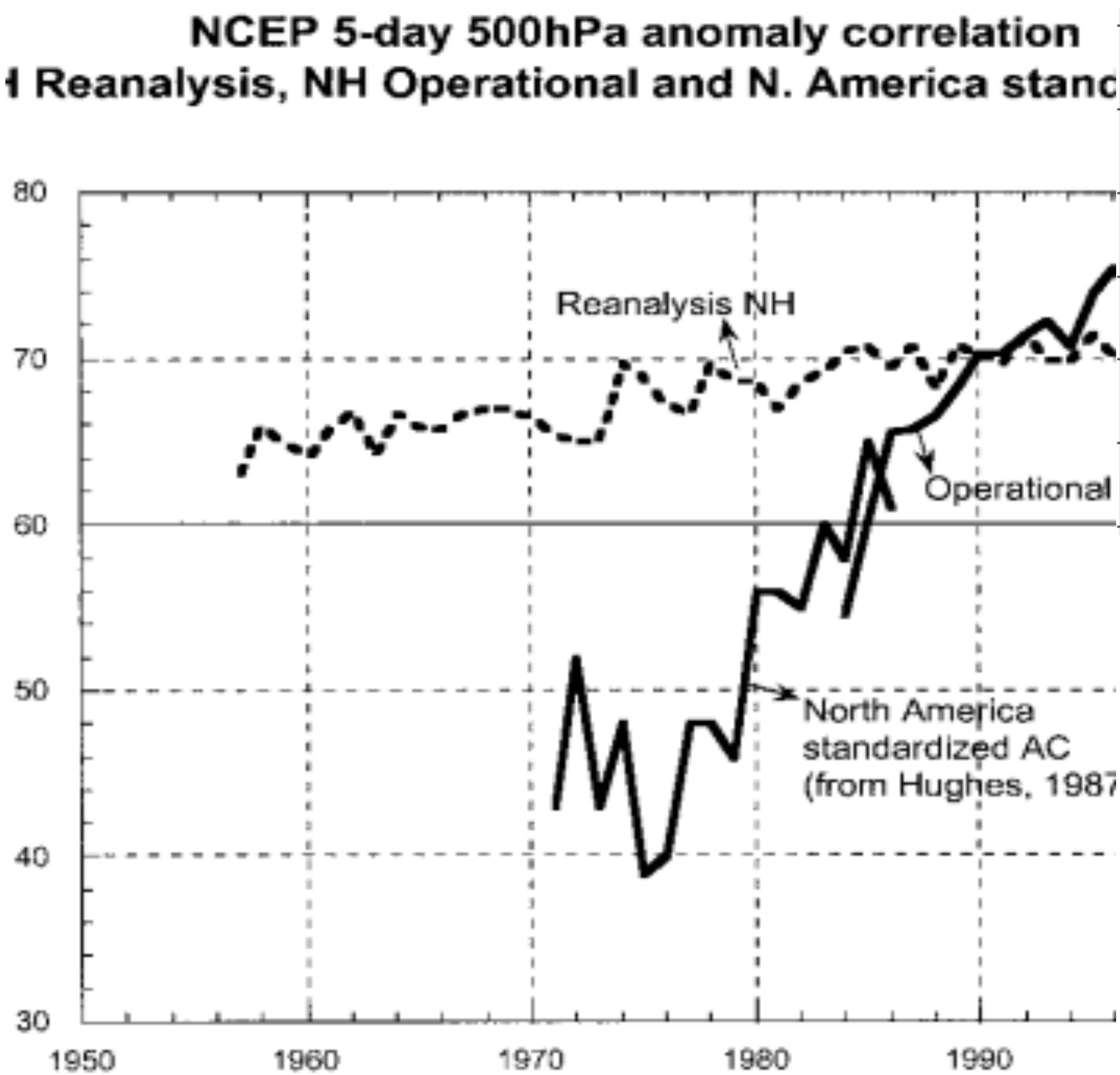
1990s HPC: Massively Parallel

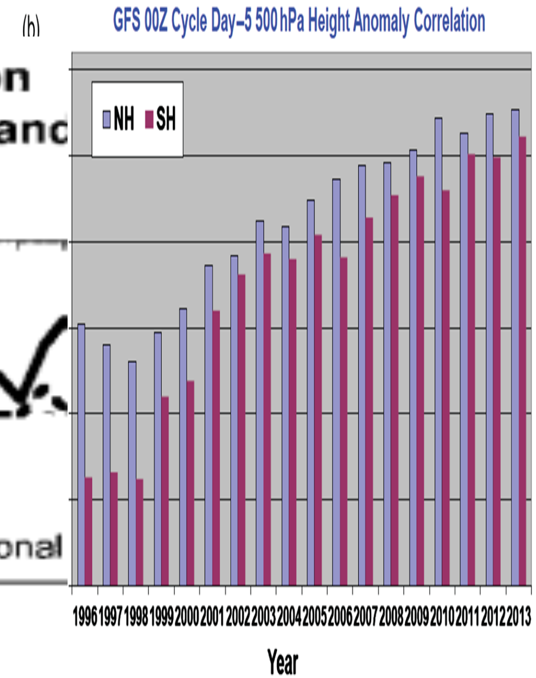
- Cray T3-E ca. 1995 – 1480 CPUs
- peak speed 1 TFLOPs
- **~2.8 billion X ENIAC**

2010s HPC: PetaFLOPs (approaching 1M cores)

- Titan at the Oak Ridge Leadership Computing Facility: hybrid-architecture Cray XK7 system
- 200 cabinets, 18688 nodes, 299K cores with a theoretical peak performance > 27 petaflops
- **~ 75 trillion X ENIAC (each core is ~250 million X ENIAC)**
- **NB: near 100% of peak realizable on ENIAC; less than 5% of Titan peak realizable**

Trends in the skill of weather prediction at NCEP (Day-5)





Kalnay et al. 1998 (BAMS, 2753-2769)

Stern and Davidson Quart. J. Roy. Meteor. Soc. 141, 2726-2736, 25 MAY 2015 DOI: 10.1002/qj.2559

Climate Model Complexity